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The Thermophysiology of Uncompensable Heat Stress

Physiological Manipulations and Individual Characteristics

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Abstract

In many athletic and occupational settings, the wearing of protective clothing in warm or hot environments creates conditions of uncompensable heat stress where the body is unable to maintain a thermal steady state. Therefore, special precautions must be taken to minimise the threat of thermal injury. Assuming that manipulations known to reduce thermoregulatory strain during compensable heat stress would be equally effective in an uncompensable heat stress environment is not valid. In this review, we discuss the impact of hydration status, aerobic

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fitness, endurance training, heat acclimation, gender, menstrual cycle, oral contraceptive use, body composition and circadian rhythm on heat tolerance while wearing protective clothing in hot environments. The most effective countermeasure is ensuring that the individual is adequately hydrated both before and throughout the exercise or work session. In contrast, neither short term aerobic training or heat acclimation significantly improve exercise-heat tolerance during uncompensable heat stress. While short term aerobic training is relatively ineffective, long term improvements in physical fitness appear to provide some degree of protection. Individuals with higher proportions of body fat have a lower heat tolerance because of a reduced capacity to store heat. Women not using oral contraceptives are at a thermoregulatory disadvantage during the luteal phase of the menstrual cycle. The use of oral contraceptives eliminates any differences in heat tolerance throughout the menstrual cycle but tolerance is reduced during the quasi-follicular phase compared with non-users. Diurnal variations in resting core temperature do not appear to influence tolerance to uncompensable heat stress.

Humans are homeothermic creatures, and regulate their body temperature within a narrow range over the entire course of their lives.[1] When heat is generated by increased metabolic activity, humans are generally successful in maintaining a thermal steady state by activating heat-loss mechanisms to dissipate the excess heat. However, a hot and/or humid environment imposes a major stress on the human body's ability to maintain physiological stability during exercise, due to a decrease in the thermal and water vapour pressure gradients between the body and the environment, thus impairing heat exchange.[2] Hyperthermia, and its attendant clinical symptoms of heat exhaustion and heat stroke, has become well recognised as a major risk encountered when exercising in hot environments.[3]

In many occupational (e.g. firefighters, hazardous waste disposal, military) and athletic (e.g. American football, auto racing, cricket, goalkeeping in field hockey) settings, protective clothing is required to shield the individual from environmental hazards or from injury. In these high risk settings, any increase in psychological strain or impairment in mental functioning due to the clothing may also place the individual at an increased risk of an accident.[4,5] Protective clothing, which is typically heavy, thick, multi-layered and bulky, exacerbates the challenge of thermoregulation because of a limited water vapour permeability across the clothing layers, further decreasing the rate of heat exchange.[6]

Under certain conditions of high ambient temperature and/or relative humidity, or with the wearing of clothing ensembles that restrict evaporative heat loss, the evaporative heat loss required to maintain a thermal steady state (E_{req}) can exceed the maximal evaporative capacity of the environment (E_{rmax}) during light exercise or even at rest. In these uncompensable heat stress (UHS) situations,[7] the body constantly stores heat. This results in body temperature continuing to increase until either exhaustion (or death) occurs or the severity of the set of environmental conditions decreases (i.e. seeking shade or an air-conditioned room, removing clothing layers to promote greater evaporative heat loss, being immersed in a cold water bath, etc.).

While protective clothing is being continually improved and lightened, the requirement of adequate impact or environmental protection is generally contradictory to the desire for adequate ventilation. For example, the requirement to prevent hazardous liquid and/or gaseous chemicals from penetrating a chemical ensemble is often contradictory to the desire for the dissipation of metabolically generated heat. Scientific interest in the problems of exercise and heat exhaustion with protective clothing intensified following the 1990-1991 conflict in the

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Persian Gulf, where soldiers of the Allied coalition, faced with the threat of chemical weapons, were forced to wear nuclear, biological and chemical (NBC) protective clothing that was originally intended for use in a temperate climate and not the hot desert environment. The major features of UHS, notably the biophysical interactions between clothing, the ambient environment and physiology, are similar across military, occupational and athletic protective clothing systems. Therefore, we feel confident in generalising military-based research to protective clothing in general.

One approach to the problem of UHS is to explore the physiology of the human inside the clothing ensemble. Performance and heat tolerance are influenced by such individual factors as gender, age and anthropometry. Furthermore, physiological manipulations such as hydration, training, fitness or heat acclimation may significantly affect individual responses to heat stress. A large body of research exists on the effects of these factors in situations where heat transfer is not impaired by clothing. However, these findings may not directly transfer over to situations where protective clothing is worn, due to the impact of clothing on heat exchange.[2,6,8-15] This review will focus on the thermophysiology of the UHS environment present when exercising with protective clothing in the heat, and explore the influence of individual characteristics and the efficacy of physiological manipulations. Although we[10,15] and others[9,11] have published reviews that have addressed the impact of protective clothing on temperature regulation, a review has not been published that encompasses the impact of physiological manipulations and individual characteristics on thermoregulation specific to the UHS environment.

1. The Uncompensable Heat Stress Environment

1.1 Heat Exchange and Heat Tolerance

Mechanisms of heat transfer are grouped into 2 general categories consisting of dry (radiative, conductive, convective) and wet (evaporative) pathways. Dry heat exchange is dependent on the temperature gradients within the organism (e.g. core to periphery) and also between the organism and the environment. In addition, the rate of cutaneous blood flow to transport heat from the core to the periphery influences the degree of convective heat exchange. Wet heat loss arises from the evaporation of water, typically secreted by the sweat glands within the skin. The potential for evaporative heat loss is determined primarily by the water vapour pressure gradient between the body surface and the environment, which in turn may be modified both by the environment and clothing[16-21] as well as physiologically due to alterations in sweat gland activity and output.[22-24]

1.1.1 Required Evaporative Cooling

This term represents the rate of evaporative cooling required to balance the summation of all other sources of heat gains and losses by the body as shown in the following equation:

$$E_{req} = M - W \pm (C + R + K) \pm (C_{resp} - E_{resp}) \quad \text{(Eq. 1)}$$

where M is the metabolic rate, W represents the rate of heat loss from the generation of external power, R, C and K are the rates of radiative, convective and conductive heat transfer, respectively, C_{resp} defines convective heat transfer through respiration and E_{resp} represents evaporative heat loss with respiration. For equations that can be used to derive each of these terms, the reader is referred to other publications.[15,21,25,26] Of note is the following equation used to estimate R and C when protective clothing is worn.[27]

$$R + C = (T_{db} - \bar{T}_{sk}) \cdot I_T^{-1} \quad \text{(Eq. 2)}$$

where T_{db} is the dry bulb temperature of the environment, $\bar{T}_{sk}$ represents mean skin temperature and I_T defines the total insulative value or thermal resistance of the clothing ensemble ($m^2 \cdot °C/W$) determined at a given wind speed with a heated and dry articulated manikin.

1.1.2 Maximum Evaporative Capacity of the Environment

This term defines the maximum cooling power of sweat evaporation at the skin surface given a

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particular environmental temperature and relative humidity. When protective clothing is worn, the following equation can be used [27]

$$E_{max} = LR \cdot i_m \cdot I_T^{-1} \cdot (P_{sk} - P_a) \quad \text{(Eq 3)}$$

where LR is the Lewis relation (16.5°C/kPa), i_m is the water vapour permeability coefficient (dimensionless) determined with a heated and wetted articulated manikin, P_{sk} represents the saturated skin vapour pressure at $\bar{T}_{sk}$ and P_a defines the ambient water vapour pressure.

UHS is defined as environments where the heat stress index (HSI = E_{req}/E_{max}) exceeds 1.0. When HSI ≤ 1.0, the E_{max} equals or exceeds E_{req}, resulting in no net storage of heat in the body and a compensable heat stress (CHS) environment.

1.1.3 Heat Tolerance

Tolerance time is defined as the time required to reach one of several end-point criteria during the UHS exposure. The exact end-point criteria are typically driven by ethical considerations or by experimental design, and may therefore vary at different laboratories or even within the same laboratory from one experiment to another. Typically, ethical constraints revolve around the allowable increase in core temperature and heart rate; for example, this increase in rectal temperature (T_{re}) can vary by at least 1°C with typical ceilings reported between 39.0 and 40.0°C.[28-31] In addition, other factors such as nausea, ataxia, syncope, voluntary termination or a maximum length of exposure may define tolerance time. Because of these different end-point criteria, comparison of tolerance times among studies or even within the same study before and after an experimental treatment must be approached with caution. Tolerance time can be influenced by the initial and final T_{re}, the heat capacity of the body ($C_{p,b}$) and the rate of heat storage (S) as shown in the following equation:

$$\text{Tolerance time} = (T_{re\ final} - T_{re\ initial}) \cdot C_{p\,b} \cdot \text{mass} \cdot (S \cdot 60 \cdot A_D)^{-1} \quad \text{(Eq 4)}$$

where tolerance time is expressed in minutes, $C_{p,b}$ is in J/kg/°C and A_D represents the body surface area (m^2).

There is not a uniform consensus among thermal physiologists as to how to define heat tolerance. Some researchers prefer to define the term as the highest core temperature that can be tolerated prior to exhaustion,[30,32,33] whereas others prefer to define heat tolerance in terms of an increase in body heat storage (S).[34] With the former definition, heat tolerance is affected only by those factors that alter the core temperature tolerated at exhaustion, while with the latter definition, factors that influence both the initial and final core temperature, as well as the heat capacity of the body, would affect heat tolerance.

1.2 Protective Clothing

Protective clothing is an ensemble designed to protect the human body from the ambient environment. For the purposes of this review, we shall define protective clothing as a system that nearly or fully covers the body, encapsulates the head and significantly impairs heat transfer due to its high insulation and low water vapour permeability. With significant heat exchange occurring through the head,[35] coverage or encapsulation of the head with helmets and/or respirators may be a major contributing factor to heat storage and the pathology of heat illness in hot environments. The nuclear, biological and chemical (NBC) protective clothing worn by the Canadian Forces, typical of environmental protective suits worn by other military forces and in many industrial settings, is one example of a multilayered clothing ensemble with a high insulative capacity and a low water vapour permeability. This system consists of, in addition to the standard underwear and operational clothing, a respirator, semipermeable hooded overgarment and impermeable rubber boots and gloves. Total mass of the ensemble is approximately 6kg. In order to allow some sweat evaporation, there is a limited mass penetration of charcoal-filtered air through the fabric. Thermal resistance (I_T) and the Woodcock vapour permeability coefficient (i_m) of the ensemble determined on a heated and wetted manikin at a wind speed of 1.12 m/s were 0.291 $m^2 \cdot °C/W$ (1.88 clo) and 0.33, respectively.[36]

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Protective clothing has a significant effect on the thermoregulatory strain experienced during exercise through both an increase in heat production and an impairment of heat dissipation. For example, wearing NBC protective clothing can result in a 13 to 18% increase in metabolic rate and internal heat production compared with normal operational clothing during treadmill exercise.[37-40] Part of the increase in metabolic rate is due to the added weight of the protective clothing. However, other factors such as friction between clothing layers and the bulkiness of the clothing alter gait mechanics and the efficiency of movement. These factors also contribute to the increase in metabolic rate, which has been shown to be significantly higher while wearing protective clothing compared to carrying an equivalent weight.[38,41,42]

When unclothed, the regulation of thermal energy exchanges between humans and the ambient environment can occur directly across the skin. However, when clothing is worn an air layer is formed directly above the skin surface, and this microenvironment forms the initial environmental layer between the body and the environment. The volume of this microenvironment formed between the clothing and skin can be as large as 50L for industrial protective clothing.[43] Multiple clothing layers form a successive series of microenvironments, each with its own thermal characteristics of temperature and humidity, through which metabolically generated heat must pass before being dissipated to the ambient environment.[9,44] Therefore, the thermal properties of clothing, such as its insulation, ventilation and permeability to water vapour, have a significant influence on the rate of heat transfer between the skin and the ambient environment.[2,9,13]

When the temperature of the ambient environment is similar to that found at the skin, as is the case during exercise in the heat at approximately 35 to 40°C while wearing protective clothing,[10] the primary pathway for heat dissipation is from the evaporation of secreted sweat.[45] Maximal evaporative heat dissipation from the body occurs when secreted sweat is vapourised at the skin.[46] When wearing protective clothing, much of the sweat may become absorbed into the clothing and trapped. The wetting or saturation of clothing by sweat may affect both the thermal or protective characteristics of the clothing and also influence the rate of heat transfer.[18-20] In addition, as illustrated in figure 1, the site of phase change may be raised above the skin due to the clothing microenvironment. In this scenario, a portion of the heat energy of vapourisation may come from the environment rather than the body, thus further decreasing the efficiency of evaporative heat loss.[11,21]

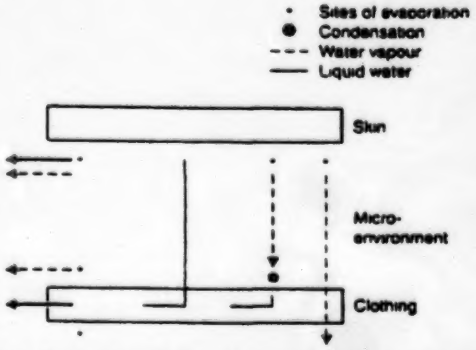

Fig. 1 Diagram of pathways for secreted sweat when clothing is worn. Note that evaporation can take place at either the skin or at several sites away from the skin (adapted from Nunneley,[11] with permission).

Due to both the elevation in metabolic heat production and a decrease in evaporative efficiency wearing protective clothing in the heat often results in an inability to dissipate generated heat and a continued storage of heat in the body. Table I presents the approximate E_{req}, E_{max} and the HSI values for an individual wearing the Canadian Forces NBC clothing while at rest or working in a warm and a hot environment. As demonstrated in the table, due to the reduced permeability to water vapour and limited capacity for evaporative heat dissipation through the NBC protective clothing, even light exercise [an oxygen uptake (VO_2) less than 1.0 L/min or approximately 25 to 30% of maximal oxygen uptake (VO_{2max}) for a 75kg male with a VO_{2max} of 50 ml/kg/min] in a warm environment or very light exercise in a hot environment can produce a HSI

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Table I. A comparison of the heat stress index (HSI) in different environments (assuming ambient vapour pressure of 1.0 and 2.2 kPa, respectively) for an individual (assuming surface area of 2.0 m^2) at metabolic rates for the military (assuming a respiratory exchange ratio of 0.85) while wearing the Canadian Forces nuclear, biological, and chemical protective ensemble (thermal resistance and vapour permeability coefficient of 0.291 $m^2 \cdot °C/W$ (1.88 clo) and 0.33, respectively). Skin temperature in all conditions was assumed to be constant at 37.0°C. External work and convective and evaporative heat exchange from the respiratory tract was assumed to be nonexistent. The evaporative heat loss required to maintain thermal steady state (E_{req}) was divided by the maximal evaporative heat loss possible in the environment (E_{max}) to obtain HSI. A HSI < 1.0 indicates a compensable heat stress, while a HSI>1.0 indicates a positive rate of heat storage within the body and an uncompensable heat stress.

Metabolic rate (VO_2, L/min)		30°C, 10% RH (W/m^2)	HSI	40°C, 30% RH (W/m^2)	HSI
Very light	E_{req}	60	0.83	95	1.36
(0.5)	E_{max}	95		70	
Light	E_{req}	145	1.53	180	2.57
(1.0)	E_{max}	95		70	
Moderate	E_{req}	230	2.42	265	3.79
(1.5)	E_{max}	95		70	
Heavy	E_{req}	315	3.32	350	5.00
(2.0)	E_{max}	95		70	

> 1.0, producing a situation of uncompensable heat stress and continued heat storage in the body.[9,47] Indeed, the impairment of heat transfer while wearing NBC clothing in the heat has been reported to be so severe that body heat storage and an increase in core temperature could exist even under resting conditions.[47]

1.3 Effects on Heat Tolerance

Heat tolerance can be reduced substantially when protective clothing is worn compared with a clothing configuration, such as normal operational clothing, which provides a more effective heat exchange with the environment.[48] Even in a thermoneutral ambient environment, firefighting or vapour protective clothing increased heart rate, core and skin temperatures, and rating of perceived exertion (RPE).[49-52] At either light or heavy work intensities, the use of NBC clothing dramatically reduced tolerance time compared with combat clothing alone.[32,47,53] The importance of protective clothing in determining exercise-heat tolerance is further demonstrated by the significant attenuation of physiological strain and/or increased tolerance time during partial encapsulation. This may be achieved by the removal of components of the NBC ensemble, notably the respirator and helmet, and unzipping the overgarment,[32,47,53,54] or the removal of the underlying combat clothing layer.[55,56] In contrast, the use of rest breaks or intermittent exercise in UHS environments while maintaining full encapsulation may be ineffective in prolonging tolerance time, due to the continued positive heat storage during the rest periods.[57]

The kinetics of evaporative heat loss are largely established by the characteristics of the clothing.[18,19,21] With exercise in protective clothing, situations may arise where the rate of heat storage and heat tolerance are governed primarily by the rate of heat production and not by environmental conditions.[47] In these situations, variations in ambient water vapour pressure, which help to establish the gradient for evaporative heat loss, may have little impact on heat tolerance.[47] Craig et al.[58] and Shvartz and Benor[59] first reported a hyperbolic relationship between voluntary tolerance time and the rate of heat storage. The curvilinear relationship between tolerance time and metabolic rate for different ambient temperatures and water vapour pressures while wearing NBC protective clothing is shown in figure 2. Each of these curves is accurately defined by a hyperbolic function where the vertical asymptote of the equation defines the metabolic rate that delineates compensable and uncompensable heat stress.[21,47,53,55] Since, by definition, UHS is accompanied by a continued increase in body heat storage, tolerance time is finite. Con-

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versely, during compensable heat stress increases in body heat content, in theory, do not limit performance and tolerance times are infinite

Figure 2 is also divided into work intensities classified as light (less than 325W or about 160 to 170 W/m^2), moderate (between 325 and 500W) and heavy (greater than 500W or approximately 250 W/m^2) according to guidelines adopted for the US military.[36] As the rate of heat production increases, it is apparent from figure 2 that variations in temperature and water vapour pressure have less of an impact on tolerance time. At work intensities above 450 to 500W, tolerance times converge at approximately 50 minutes. Differences in tolerance time among different ambient conditions are noticeable at lighter metabolic rates. This is because any change in E_{max} due to a change in the ambient vapour pressure represents a smaller percentage of E_{req} at higher metabolic rates For example, in hot and dry environments, E_{max} would be estimated at about 100 W/m^2 for the NBC protective ensemble but this value would decrease to 30 W/m^2 in more humid conditions.[21] This decrease in E_{max} of 70 W/m^2 between the dry and humid environments represents approximately 25 to 30% of the heat produced during heavy exercise but 45 to 50% of the heat produced during light exercise. Recent evidence from our laboratory has shown also that 20 to 40 minutes of exercise are required before the vapour pressure gradients at the skin surface are similar to those defined by E_{max}.[21,63] Thus, some time is required to establish maximal vapour pressure gradients and evaporative heat loss to the environment through the clothing layers We have also reported some variation in tolerance time at heavy work intensities between low and high ambient humidity, though the variation remained greater at lower exercise intensities.[21]

Also shown in figure 2 are results from other investigations that have examined work tolerance time in different NBC protective ensembles.[32 54 57 60-62] It is noteworthy that these other studies have primarily focused their efforts at work intensities classified in military and occupational guidelines as moderate or heavy However, our data have shown

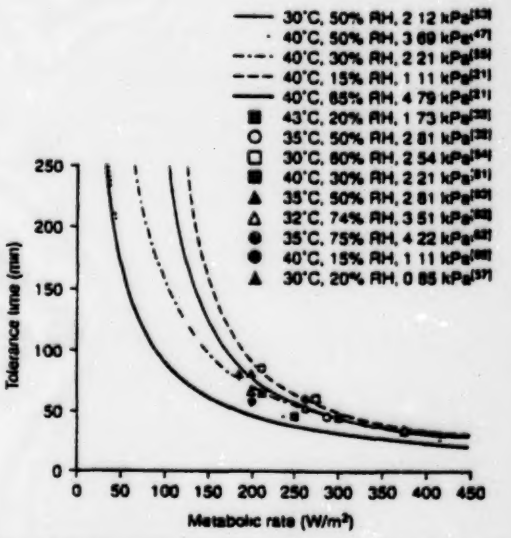

Fig. 2. The decreasing curvilinear relationships between tolerance time and metabolic rate established from studies by McLellan et al.[21 47 53,58] Also shown are discreet data points from other published studies [32,54,57 60-62]

differential effects of rehydration (see section 2.1 2), heat acclimation (see section 2.2) and ambient vapour pressure (see above) on tolerance time during light and heavy metabolic rates. As a result, we have chosen light exercise intensities to evaluate our most recent attempts to manipulate thermoregulation and tolerance time when the protective clothing is worn. We feel exposure times in excess of 60 minutes reduce the risk of making a type II error when differences in heat transfer through the clothing and physiological strain are analysed for a given treatment effect.

2. Physiological Manipulations

Humans adapt to environmental stressors through complex interactions between physiological and psychological factors [64] Thermal stress may significantly impair human cognition and behaviour, thereby increasing the risk of accidents This impairment may remain even upon partial physiological adaptation.[65] Therefore, while this review con-

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centrates on physiological responses to UHS, psychological and ergonomic factors should also be accounted for when determining the readiness of an individual to work or compete in hot environments

Previous exposure to a hot environment is arguably the most specific and direct method of adaptation to exercise in the heat.[66] A high level of aerobic fitness has also been associated with an improved exercise-heat tolerance, and physical training is another treatment that has been used in an attempt to adapt individuals to work in a CHS environment [67] Primary amongst the adaptations to CHS appear to be alterations in the body's fluid compartments and overall fluid balance, with an increase in plasma volume a consistent response to both physical training and heat acclimation protocols [67] In turn, improvements in body fluid balance with manipulation of hydration status may result in the classic description of an individual who is adapted to hot environments, including the maintenance of a heightened sweating response, a lowered heart rate and a lowered internal body temperature [17 68-70]

A high level of aerobic fitness or physiological treatments, such as aerobic training and heat acclimation, may be of limited effectiveness in decreasing physiological strain or prolonging tolerance during exercise-heat stress with protective clothing. Due to the limited evaporative heat loss possible through the clothing, the increased sweat production associated with aerobic fitness, training or heat acclimation[69,71] may not result in an increased evaporative heat loss when wearing protective clothing. Rather, the elevated sweat rate may potentiate the rate of dehydration.[72]

2.1 Hydration Status

Water balance during exercise is determined by a multitude of factors, including the environmental conditions, the nature and intensity of exercise and the characteristics of the fluid replacement [73-75] Two terms related to hydration status that are often mistakenly used interchangeably are dehydration and hypohydration For the present work, dehydration will be defined as the dynamic loss of body water due to sweating over the course of exercise without fluid replacement, or where fluid replacement does not match the rate of fluid loss In contrast, hypohydration will refer to the state or level of hydration after the loss of a certain amount of body water from the body As an example of the differences between the 2 terms, a wrestler may dehydrate himself through exercise without fluid intake to make a certain weight category, then compete in the actual event in a hypohydrated state

Voluntary loss of bodyweight and water is often used by athletes to achieve a certain weight category prior to an athletic event. Typically, some time occurs between the weigh-in and competition, in which athletes attempt to restore the lost bodyweight. The practice of voluntarily dehydrating to reach a weight category should be balanced with the possible decrements in performance due to exercising in a hypohydrated state. Alternatively, in an industrial setting, inadequate time for recovery and rehydration may be an unintentional or unavoidable cause of hypohydration prior to a subsequent work session. The contribution of lowered hydration status to the pathology of hyperthermia and heat illnesses may be magnified when wearing protective clothing, due to the further impairment of evaporative heat loss present with protective clothing.

Sweat rates exceeding 1 L/h are typical during moderate exercise, with a high of 3 7 L/h having been recorded during the 1984 Olympic Marathon.[76] Wearing protective clothing may magnify the risk of dehydration, due to heat storage within the body and the increasing core temperature further stimulating the sweating response To a certain extent, mild dehydration during exercise is psychologically tolerated by an individual [77-83] Even with an adequate fluid supply, the rate of *ad libitum* fluid intake rarely matches the rate at which fluid is lost, and an individual will gradually dehydrate [77,82] An involuntary dehydration of 2% or more of bodyweight may occur before a strong drinking response is observed [73,77]

Altered hydration status likely affects the cardiovascular and thermoregulatory response to exercise

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via either a decrease in blood volume or an increase in osmolality. A progressive decrease in plasma volume during exercise in the heat resulted in an increased heart rate and esophageal temperature (T_{es}) independent of changes in osmolality.[84] Following a drop in blood volume, the competition for blood flow between metabolic and thermoregulatory demands during exercise was increased.[70] One compensation to maintain central circulation and cardiac filling pressure is a reduction in cutaneous circulation and, hence, in heat transfer from the core to the periphery. The ability for dry heat exchange appears to be especially sensitive to blood volume changes.[85-88] There are separate core temperature thresholds for the onset of cutaneous vasodilation and sweating and each of these thresholds is affected separately by changes in blood volume and osmolality. For example, the core temperature threshold at which vasodilation and maximal skin blood flow (SkBF) occurred was decreased following isosmotic hypovolemia induced by diuretics.[87] In contrast, hyperosmotic hypovolemia resulted in an impairment in the sensitivity (or slope) of the SkBF response to increasing core temperature and a lower maximum SkBF compared with hyperosmotic isovolemia.[89] In addition to decreasing cutaneous blood flow, a drop in blood volume alone also impaired the sensitivity of the sweating response, although no differences were observed in the core temperature threshold for sweating.[90]

2.1.1 Hypohydration

It is well documented that fluid replacement and hydration status are important determinants of heat tolerance when evaporative heat loss is not restricted by clothing.[74,75,91-93] The additional physiological stresses imposed by hypohydration appear to potentiate the effects of heat stress and severely impair the ability of individuals to tolerate exercise. A critical hypohydration threshold for exercise impairment does not appear to exist in the heat, where even relatively minor levels of hypohydration are sufficient to reduce exercise-heat tolerance.[94] Core temperature and heart rate responses increased with progressive severity of hypohydration, while sweat rate response for a given core temperature decreased.[95] At 5% hypohydration termination of exercise due to individual intolerance occurred at a significantly lower core temperature than while euhydrated.[13]

The magnitude of cardiovascular and thermoregulatory impairment due to hypohydration during exercise in the heat appears to be graded in proportion to the severity of hypohydration. This may be partially due to a progressive impairment of evaporative heat loss ability, with increasing levels of hypohydration both increasing the core temperature threshold for the initiation of sweating and also decreasing the sensitivity of the sweating response.[95,96] Strydom and Holdsworth[97] observed increased core temperatures in 2 miners at high (5 to 8% bodyweight) versus low (3 to 5%) levels of hypohydration. Sawka et al[95] systematically compared the effects of hypohydration levels of 0, 3, 5 and 7% bodyweight during exercise in the heat. Plasma volume prior to and during exercise was progressively decreased at 3 and 5% hypohydration compared with euhydration, with an apparent plasma volume defence beyond 5% resulting in no further decrease in plasma volume at 7% hypohydration. Comparing the 4 hydration levels, core temperature linearly increased by approximately 0.15°C and heart rate increased 4 beats/min with each percentage decrease in body mass. The increased core temperature and heat storage appear to be largely mediated by an impaired heat loss capacity, as the sweating rate at a given core temperature also decreased for each increasing level of hypohydration. As a result of the increased cardiovascular and thermoregulatory strain, voluntee exhaustion began occurring before the completion of the exercise sessions at 5 and 7% hypohydration.

Sawka et al[33] reported that hypohydration of 8% total body water, or about 5% body mass, significantly decreased plasma volume and contributed to a decreased sweating rate and greater heart rate during exercise in a hot and dry environment. Heart rates were significantly higher at exhaustion during the hypohydration condition despite a greatly decreased endurance time to exhaustion (from 12 to 55 minutes), demonstrating a dramatic increase

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in cardiovascular strain with hypohydration. In addition, the core temperature at which exhaustion occurred was significantly reduced by hypohydration from 39.1 to 38.7°C, possibly due to a shorter time allowed for heat buildup or else an alteration in the central integration of temperature inputs. An increased T_{re} and heart rate during exercise, along with a decreased sweating rate at a given core temperature, occurred when hypohydrated by 5% bodyweight during exercise in a hot (49°C) and dry (20% relative humidity) environment.[98] Evaporative heat loss capacity roughly matched heat loss requirements in these latter 2 studies, with a HSI of approximately 1.0.

Hypohydration also significantly impaired exercise-heat tolerance in uncompensable heat stress environments. While wearing protective clothing in a 40°C, 30% relative humidity environment, hypohydration of 2.5% body mass resulted in significantly shorter tolerance times while exercising at intensities that elicited HSI = 2.5 (from 107 to 93 minutes) and 3.5 (from 60 to 53 minutes).[99] Furthermore, when wearing protective clothing in the heat, impairments in physiological responses and tolerance while hypohydrated were consistently observed regardless of aerobic fitness, exercise intensity or any physiological manipulations such as aerobic training and heat acclimation.[99-101] This would suggest that the maintenance of proper body fluid balance should be the primary concern when exercising with protective clothing.

2.1.2 Fluid Replacement

Fluid replacement during exercise contributes to the maintenance of plasma volume during exercise, aiding thermal and cardiovascular homeostasis.[92,93] In a warm (32°C) environment, Montain and Coyle[102] elicited graded levels of dehydration during 2 hours of moderate cycling exercise by varying the amount of fluid replacement from 0 to 100% of sweating rate. Graded dehydration resulted in graded physiological responses, including increases in heart rate, decreases in stroke volume, increases in T_{es}, decreases in skin blood flow and increases in RPE.[102] The importance of fluid replacement was also illustrated by Candas et al.[92] During prolonged exercise in the heat, heart rate and T_{re} were significantly higher beyond 2 hours in volunteers who were initially euhydrated but given no fluid replacement compared with when they were 2% hypohydrated prior to the exercise but given fluid replacement throughout.

However, ingested fluid must first be emptied from the stomach and absorbed in the intestine before it can enter the body and affect exercise response. Transit time is dependent on many factors including volume ingested, exercise intensity and ambient temperature.[103] Gastric emptying is a dynamic function that is affected by many different factors. Balanced against ingesting large volumes of fluid to prevent dehydration is the danger of large gastric volumes causing discomfort and impaired performance.[104] This is especially dangerous if either heat exposure or exercise impairs gastric emptying. With an increase in exercise intensity, the decreased splanchnic blood flow due to increased metabolic demands for muscle blood flow has been assumed to inhibit gastric emptying and intestinal absorption.[70] Rather than a progressive decrease in the rate of gastric emptying with increasing exercise intensity, Neufer et al.[105] observed an increase in gastric emptying when walking or running at < 70% $\dot{V}O_{2max}$ compared with resting values, possibly due to an increase in stomach motility from the walking motion. Only at exercise intensities > 70% $\dot{V}O_{2max}$ was the rate of gastric emptying decreased. Fordtran and Saltin[106] found no impairment in gastric emptying of a glucose solution while exercising at 71% $\dot{V}O_{2max}$ on the treadmill. Thermal strain decreased gastric emptying rate, with a lower rate being observed when exercising at 49°C compared with 18°C.[107] While a period of heat acclimation had no effect on the rate of emptying from the stomach, hypohydration of 5% body mass decreased the rate of gastric emptying.[107]

While wearing protective clothing, it is possible that the influence of fluid replacement may be masked by the high rate of heat storage and short tolerance times at high exercise intensities. At metabolic rates above 500W, tolerance times converge at approximately 50 minutes for a range of ambient

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environments and physiological manipulations [21] Therefore, it may be the case that fluid replacement may be beneficial only during relatively light exercise, where tolerance time is long enough to allow a significant amount of fluid to enter the body and affect responses before exhaustion occurs from other factors. We recently reported support for this hypothesis [99] While wearing protective clothing in a hot environment, fluid ingestion during exercise significantly prolonged exercise tolerance (from 93 to 107 minutes) at light exercise intensities (HSI approximately 2 5) In contrast, tolerance times (from 58 to 60 minutes) at higher intensities (HSI approximately 3.5) were unaffected by fluid ingestion

2.1.3 Hyperhydration

Hyperhydration, a steady state increase in total body fluid balance, has also been explored as an ergogenic manipulation prior to exercise-heat stress in both compensable and uncompensable heat stress environments An expansion in plasma volume and total body water has been induced through chronic water loading for about 1 week, resulting in slightly lower core temperatures during exercise-heat stress [108-110] Forced water loading did not improve muscle strength, muscle fatiguability or performance times of soccer drills.[108] However, 15km cycling times were significantly improved in a hyperhydrated state [109] The authors attributed this improvement to the ability to work at a higher percentage of VO_{2max}, supported by the higher heart rates during the test while hyperhydrated

Single and multiple ingestions of glycerol have also been used to produce hyperhydration,[30,111-114] with the proposed mechanism of action being an increased rate of water reabsorption at the kidneys [111] A short term increase in total body water of approximately 1.5L has been reported with glycerol ingestion, though the effects on plasma volume may be minimal and masked by other factors [112] Glycerol ingestion improved endurance times during steady-state cycling.[114] However, beyond delaying the onset of body water deficits, the efficacy of hyperhydration to improve exercise-heat tolerance appears to be minimal. Latzka et al.[30,112] reported that, compared with an euhydrated state, hyperhydration by either water loading or glycerol ingestion did not provide any major improvements in T_{re}, skin temperature, sweating responses or heart rates during either compensable or uncompensable heat stress exposures In addition, glycerol ingestion may have adverse effects, including nausea and headaches.[115]

2.2 Heat Acclimation

Classic adaptations following heat acclimation include an increase in sweating response and a decrease in heart rate, core and skin temperature, and perceived exertion during exercise in the heat.[68-70] Epidemiological evidence supporting the efficacy of heat acclimatisation was provided in a long term clinical study on Marine Corps recruits Despite a hotter average weather pattern in September, the incidence of exertional heat illnesses was significantly lower than at the start of the hot season in May, when the recruits were theoretically unacclimatised to the heat.[116] In situations of compensable heat stress, even short acclimation periods appear to be sufficient for significant reductions in physiological strain. Major cardiovascular and thermoregulatory adaptations occurred during the first few days of repeated heat exposures, with almost complete adaptation being achieved within 14 days.[117-120] Heat acclimation may also be a transient phenomenon requiring repeated heat exposures to maintain the adaptations, as no acclimation effects were observed when heat exposures were separated by 1 week.[121] However, once heat acclimation is achieved, the rate of decay of the adaptations is slow, occurring over several weeks, and the reinduction of heat acclimation can be achieved rapidly [119]

Similar to physical training or an increase in fitness, heat acclimation produces a series of adaptations in the sweating response that serve to increase the rate of sweat production.[17] An increased sweating rate with heat acclimation is partly mediated at the central thermoregulatory integrators, with a reduction in the core temperature threshold for the initiation of the sweating response.[69,122] The sweating response to local electrical stimulation

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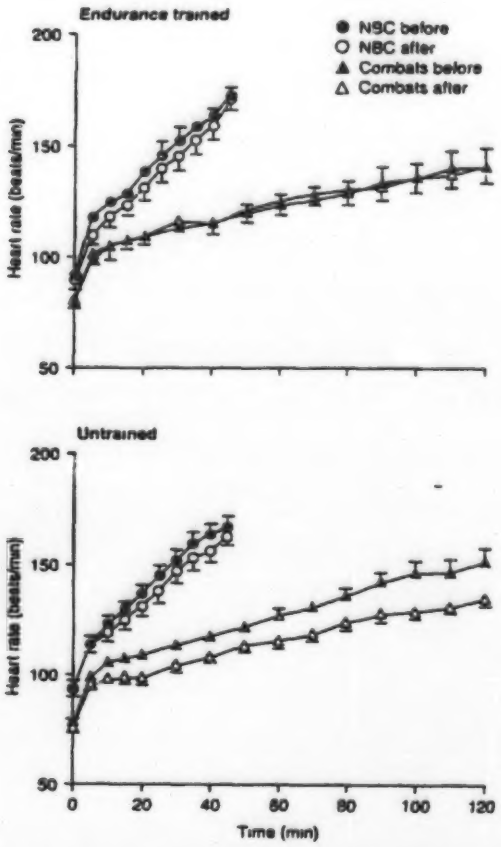

Fig. 3. Heart rate responses before and after 6 days of heat acclimation for men who had completed 8 weeks of endurance training (top) or no training (bottom) during heat stress exposure while wearing either combat clothing or a nuclear, biological and chemical (NBC) defence protective ensemble. There was a significant decrease in heart rate throughout the heat stress exposure for the untrained men only while wearing combat clothing [40]

was significantly increased following whole-body heat acclimation [123]. This appears to be an integrated whole-body response to repeated heat exposure, as neither local stimulation by itself nor local heating resulted in an increased sweat output during subsequent heat exposure.[123] In addition, Sato et al.[124] have shown both morphological and functional changes of the sweat gland following heat acclimation. The nature of the secreted sweat may also change with heat acclimation.[125] A strong inverse correlation was observed by Nose et al [126] between the loss of free water and the Na^+ in sweat. Therefore, one adaptation resulting from heat acclimation is the production of a more dilute sweat.[125,127]

In CHS environments, an elevated sweating rate would theoretically lead to an increased evaporative heat dissipation. Commander's guides for the military have implicitly assumed that the improvements in heat tolerance that follow heat acclimation to a hot-dry environment while wearing clothing that does not limit evaporative heat loss would also be evident when NBC clothing was worn. However, we[40,128,129] and others[130] have questioned whether the increased sweat rates that follow 1 to 2 weeks of hot-dry heat acclimation would be beneficial while wearing protective clothing that restricts evaporative heat loss. Aoyagi et al.[40] studied the effects of 6 days of heat acclimation alone or following 8 weeks of endurance training. The heat acclimation involved exercise at 50% $\dot{V}O_{2max}$ for 1 hour in the hot-dry test environment of 40°C and 30% relative humidity while wearing shorts, a T-shirt, socks and running shoes. Figures 3 and 4 show the heart rate and T_{re} responses, respectively, before and after heat acclimation while wearing combat clothing (a clothing configuration that allows effective heat loss to the environment through the evaporation of sweat) and the NBC protective ensemble. For those volunteers who had finished 8 weeks of endurance training, heat acclimation offered no further advantage to work in the heat while wearing the combat clothing. In contrast, for the untrained volunteers, heat acclimation decreased the T_{re} and heart rate responses throughout the 120-minute heat-stress exposure. When the NBC protective clothing was worn, heat acclimation had no effect on heart rate but lowered the initial T_{re} by approximately 0.3°C for both groups. Despite these lower T_{re} values which were maintained throughout the heat exposure, tolerance times remained unchanged at approximately 50 minutes. These findings imply that the discomfort associated with other fac-

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tors in addition to the rise in T_{re}, such as the proportion of wetted skin from increased sweat rates, may have a negative impact on tolerance times

Two concerns from this initial study were addressed in a subsequent investigation by Aoyagi et al [128] Firstly, the metabolic rate used to evaluate the effects of the heat acclimation programme while wearing the NBC clothing was decreased from 550W to less than 350W by using an intermittent work and rest schedule The lower metabolic rate effectively doubled tolerance times in the unacclimated state and, therefore, provided more time for cooling of the body to occur with the evaporation of sweat from the skin surface and the clothing layers Secondly, heat acclimation in the hot-dry environment was extended to 12 days for one group since it had been reported that changes to sweat rate and T_{re} during work in the heat require up to 2 weeks of daily heat exposure before the adaptations are complete.[117,119] When combat clothing was worn, decreases in heart rate and T_{re} during 150 minutes of continuous treadmill walking at 4 8 km/h were greater for the group that performed 12 days of heat acclimation. When the NBC protective ensemble was worn, both groups showed equal reductions in heart rate and T_{re} (figs 5 and 6) Despite significant increases in sweat rate for both groups after heat acclimation, once again the sweat evaporation from the clothing ensemble remained unchanged. The increases in tolerance time for both groups of approximately 15% from 100 to 115 minutes could be attributed to the lowering of resting T_{re} and the apparent slowing of the rate of increase of T_{re} during the heat-stress test These findings are similar to those reported by Millard et al [130] following 5 and 10 days of heat acclimation Thus, when the protective clothing is worn, extending the hot-dry heat acclimation from 5 to 6 days to 10 to 12 days does not further reduce the physiological strain. However, work time in the heat can be extended approximately 15% following the period of heat acclimation if the exercise and heat-stress challenge produces an HSI less than 3. Heavier metabolic rates or environmental conditions that increase the HSI above 3 would be expected to negate the small

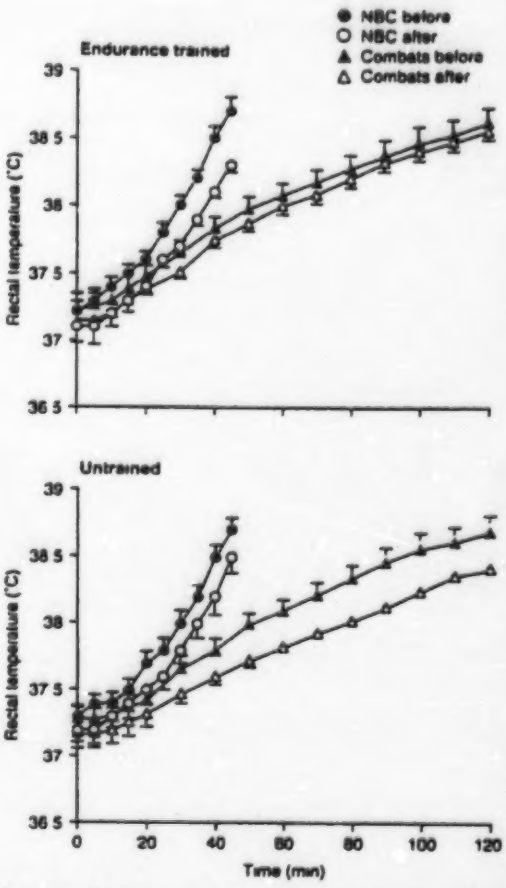

Fig. 4. Rectal temperature (T_{re}) responses before and after 8 days of heat acclimation for men who had completed 8 weeks of endurance training (top) or no training (bottom) during heat stress exposure while wearing either combat clothing or a nuclear, biological and chemical (NBC) defence protective ensemble There was a significant decrease in T_{re} throughout the heat stress exposure for the untrained men while wearing combat clothing and for both groups while wearing the NBC clothing [48]

benefits of a hot-dry heat acclimation programme when the protective clothing is worn

Heat acclimation can be achieved by a variety of heat exposure protocols In addition to the standard training variables of frequency, duration and intensity, the environment is also a significant compo-

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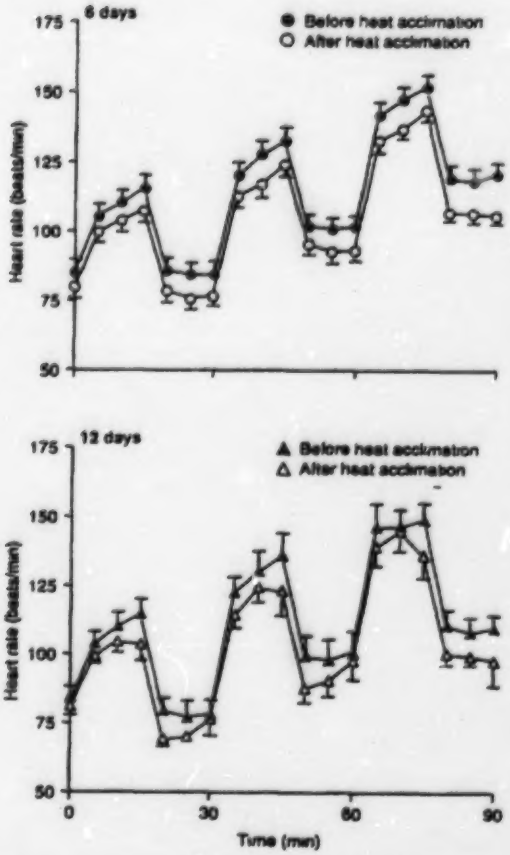

Fig. 5. Heart rate responses before and after 6 (top) or 12 (bottom) days of heat acclimation for men during heat stress exposure while wearing a nuclear, biological and chemical (NBC) defence protective ensemble. There was a significant decrease in heart rate throughout the heat stress exposure for both groups of men and the decrease was similar for both groups [129]

nent of a heat acclimation programme. Wearing heavy sweat clothing in cool environments may elicit the same increased sweating response as with heat exposures, and this has been utilised as an alternative method of heat acclimation.[131] The specificity and transferability of heat acclimation programmes using protective clothing remains controversial. Shvartz and Benor[132] and Shvartz et al.[133,134] found that significant increases in sweat rates in a hot-dry and compensable environment can be achieved following heat acclimation in cool conditions while wearing vapour-barrier suits which did not allow evaporative heat transfer. they concluded that the prevention of evaporative heat loss was a strong stimulus for sweat production and a major factor in heat acclimation. However, the ideal heat acclimation programme may be specific to both the environment that will be encountered as well as the clothing, if any, which will be worn.[135-137] Shvartz et al.[138] acclimated volunteers to either unclothed exercise in a hot-dry environment or a hot-wet environment, using vapour barrier clothing at a slightly cooler ambient temperature to achieve a similar ambient wet bulb globe temperature (WBGT). During subsequent hot-dry exercise without clothing, although both groups demonstrated an improvement, the physiological strain was significantly lower in the hot-dry compared to the hot-wet acclimation group. In contrast, Griefahn[139] recently reported an equal degree of acclimation in volunteers following exposure to 3 substantially different climates with a similar WBGT of 33.5°C. Furthermore, this acclimation was transferable to other climates. Interestingly, participants in this latter study wore minimal clothing for all experimental treatments, and it is possible that the different findings in the studies may be related to specific effects of the clothing.

Even if the ambient environment is hot and dry, the impaired evaporation of sweat and high vapour pressure would result in hot and wet conditions within the clothing microenvironment. Therefore, clothing may contribute specifically to heat acclimation by producing a high rate of skin wettedness from the nonevaporated sweat. Skin wettedness normally results in a saturation of the sweat gland and suppression of gland secretion through a process termed hidromeiosis,[140] which is normally more evident in the non heat-acclimated state.[137] Fox et al.[137] also noted that sweat suppression was more evident during a heat-tolerance test in a hot-wet environment for individuals who had acclimated to hot-dry conditions compared with those individuals who had acclimated to the hot-wet test environ-

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ment. Repeated heat exposures featuring high sweating rates and skin wettedness may produce adaptations at the level of the sweat glands, minimising hidromeiosis by allowing the glands to maintain high sweat outputs despite high skin wettedness.[17,141,142] Heat acclimation with protective clothing may also train an individual to tolerate the psychological discomfort associated with high levels of skin wettedness.[141]

A lack of transfer of hot-dry heat acclimation adaptations to a hot-wet environment appears to be true also.[143] Both of our previous studies[40,128] involved heat acclimation to the hot and dry test environment (i.e. 40°C and 30% relative humidity while wearing only operational combat clothing) followed by exercise in a hot and wet microenvironment (i.e. 40°C and 30% relative humidity wearing NBC clothing). Therefore, McLellan and Aoyagi[129] proposed that 12 days of heat acclimation while wearing the NBC clothing would have a greater impact on the changes to heat tolerance while wearing the clothing than their previous findings had indicated following acclimation to the hot and dry test environment.[40,128] Few differences were noted between the hot-wet and hot-dry acclimation groups when combat clothing was worn during the continuous treadmill walking at 40°C and 30% relative humidity. However, when the protective clothing ensemble was worn, some notable differences were found between the 2 acclimation methods. For the hot-wet heat acclimation group, there was a greater decrease in mean skin temperature, a greater slowing in the rate of increase in T_{re} (fig. 7) and a greater percentage increase in tolerance time compared with the hot-dry acclimation or control groups. Tolerance times increased 27% from 104 to 130 minutes as a result of the hot-wet heat acclimation programme compared with the 11% increase from 109 to 120 minutes that followed the 12 days of hot-dry heat acclimation. These data reveal that performance during work in the heat that involves wearing the protective clothing will be improved more following heat acclimation to the microenvironment within the protective clothing ensemble than following heat acclimation to hot-dry ambient conditions. The data also show that the 15 to 30% increases in work tolerance following heat acclimation when protective clothing is worn are far less than the 200 to 300% increases reported with a clothing configuration that does not restrict evaporative heat transfer.[144]

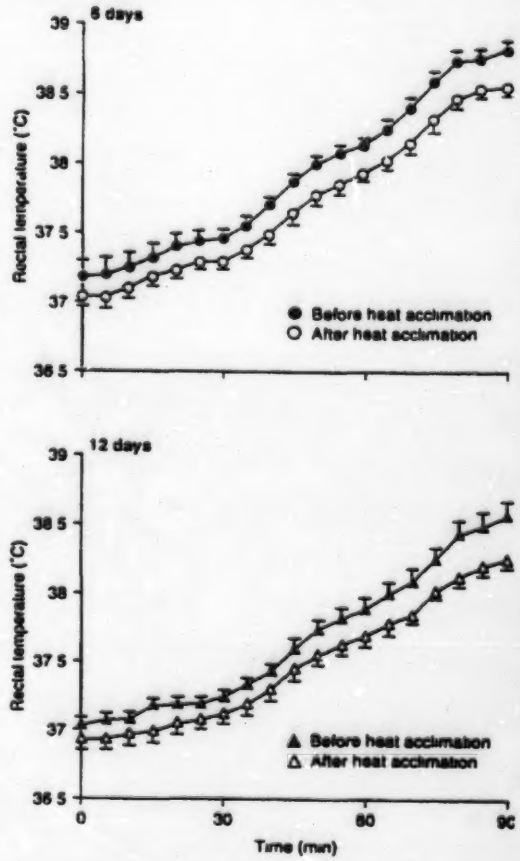

Fig. 6. Rectal temperature (T_{re}) responses before and after 6 (top) or 12 (bottom) days of heat acclimation for men during heat stress exposure while wearing a nuclear, biological and chemical (NBC) defence protective ensemble. There was a significant decrease in T_{re} throughout the heat stress exposure for both groups of men and the decrease was similar for both groups.[128]

In contrast to our previous findings,[129] we recently observed no significant improvement in

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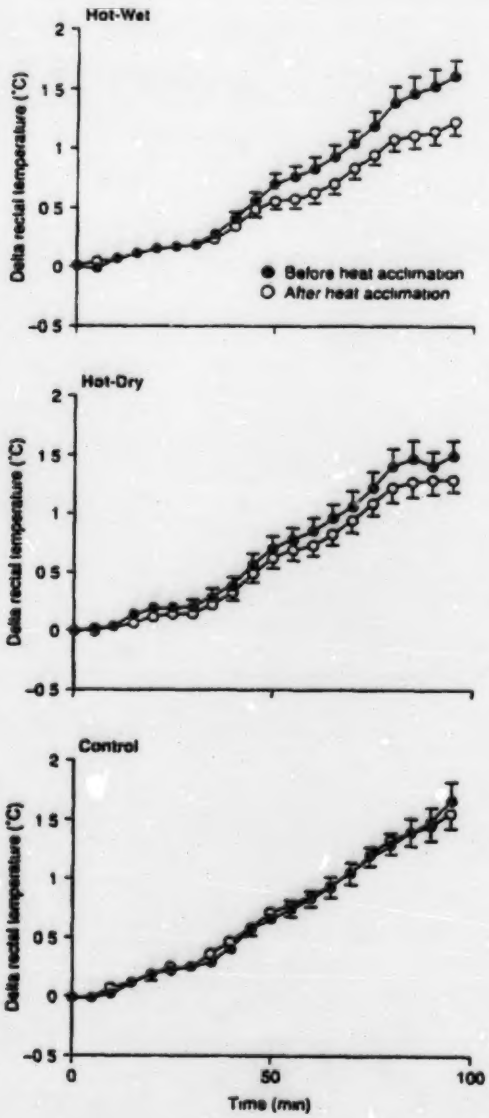

Fig. 7. Rectal temperature (T_re) responses before and after 12 days of hot-wet (top), hot-dry (middle) and no (bottom) heat acclimation for men during heat stress exposure while wearing a nuclear, biological and chemical (NBC) defence protective ensemble. There was a significant decrease in T_re for the groups that performed heat acclimation but the decrease occurred sooner and was greater for the hot-wet group.[129]

UHS tolerance times following hot-wet (40°C, 30% relative humidity with NBC clothing) heat acclimation.[100] The provision of water at regular intervals by Cheung and McLellan[100] may have caused the disparity in the effects of acclimation between our studies. Fluid replacement has been demonstrated to reduce physiological strain during exercise in the heat,[93] and specifically to decrease cardiovascular strain and increase tolerance time while exercising in the heat with NBC clothing.[99] As such, the fluid replacement may have extended exercise-heat tolerance during the pre-acclimation HST to near the maximum possible given the uncompensable heat stress environment, thereby limiting the amount of improvement that could be observed with subsequent heat acclimation. If this is the case, it would underline the importance of fluid replacement in an uncompensable heat stress environment regardless of fitness or acclimation status. The studies also differed in that Cheung and McLellan[100] utilised continuous exercise, while McLellan and Aoyagi[129] utilised intermittent (15 minutes work, 15 minutes rest) exercise. It is possible that the rest breaks may have allowed differences in water vapour transport through the clothing. However, Kraning and Gonzalez[57] reported that the heat stress remained uncompensable and heat storage continued even during rest breaks when protective clothing is worn in the heat.

2.3 Aerobic Fitness

A high level of cardiorespiratory fitness has been associated with an improved exercise-heat tolerance since the initial theoretical connection was made by Robinson et al[144] and Bean and Eichna.[145] These suggestions were based largely on anecdotal evidence, but have been largely supported by subsequent studies.[67] Piwonka et al[146] reported that trained distance runners exhibited a decreased physiological strain compared to untrained individuals during exercise-heat stress. Havenith and van Middendorp[147] reported that interindividual variations in aerobic fitness and anthropometric measures could account for a significant portion of the variance in heat storage not explained by differences in

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metabolic rate and environmental conditions. In either temperate, hot-dry,[148,149] or hot-wet environments,[150] VO_{2max} was significantly and inversely correlated with core temperature and heart rate. Henane et al [151] reported that trained and fit (VO_{2max} approximately 65 ml/kg/min) athletes had an improved sweating response and exercise-heat tolerance compared to sedentary and unfit (VO_{2max} approximately 40 ml/kg/min) individuals.

However, other studies reported only a minimal relationship between VO_{2max} and exercise-heat tolerance.[152,153] Caution must be employed when attributing improvements in exercise-heat tolerance solely to aerobic fitness. An increase in VO_{2max} is an indirect result of the physiological adaptations to training, such as changes in blood volume, cardiac function and muscle metabolism. Therefore, VO_{2max} by itself may not be a reliable indicator of exercise-heat tolerance.[67,153] The amount of regular physical activity may be a better indicator of the presence of training-induced adaptations to heat exposure.[152] The mode of training used during exercise also appears to influence the responses to exercise-heat stress. While highly trained and fit (VO_{2max} approximately 65 ml/kg/min) nordic skiers and swimmers both had higher sweat outputs than sedentary and unfit (VO_{2max} = 40 ml/kg/min) individuals, the sweating response and exercise-heat tolerance was significantly higher in the skiers compared to the swimmers.[151] The authors suggested that the greater exercise-induced hyperthermia in the skiers was responsible for the disparity in the observed adaptations.

The benefit of high aerobic fitness during clothed exercise in the heat is unclear. Smolander et al [154] reported no difference in cardiovascular or thermoregulatory strain in volunteers with a high (60 ml/kg/min), compared with a low (40 ml/kg/min) VO_{2max} while wearing light industrial clothing which permitted evaporative heat transfer. However, all volunteers exercised at 30% VO_{2max}, and relative exercise intensity may be the primary determinant of the heart rate and core temperature response.[155,156] While wearing NBC protective clothing at a standardised absolute exercise intensity, individuals with a high VO_{2max} relative to lean body mass (LBM) [75 ml/kg LBM/min] had a lower heart rate, higher sweating rate and a trend towards longer tolerance times compared to individuals of moderate (60 ml/kg LBM/min) fitness.[72] However, the relatively short tolerance times (54 and 45 minutes for the very fit and moderately fit, respectively) suggests a high metabolic rate which may have precluded significant differences (see section 1.3).

We have recently performed a cross-sectional study comparing the responses of very fit versus moderately fit individuals at a lighter level (HSI approximately 2.5) of UHS.[100] Exercise-heat tolerance was greater in highly fit (VO_{2max} > 55 ml/kg/min and physically active) compared to moderately fit (VO_{2max} < 50 ml/kg/min and sedentary) individuals, with tolerance times averaging 110 and 88 minutes in highly fit and moderately fit, respectively. All participants walked at the same speed of 3.5 km/h so the more fit individuals were exercising at a lower %VO_{2max}. Nevertheless, individual differences in tolerance time are more closely related to an absolute rather than to a relative expression of metabolic rate (see fig. 2) because of the limits to evaporative heat loss created by the clothing layers. Interestingly, distinct differences between fitness groups were observed in the reasons for ending the experiment and also in both the initial T_{re} and the final T_{re} at which volunteers terminated the experiment. The highly fit volunteers generally terminated the trials due to their T_{re} reaching our ethical limit of 39.3°C and felt they could have continued. In contrast, the moderately fit volunteers predominantly ended the trial due to exhaustion, with an average final T_{re} of 38.6°C. Overall, our observations on UHS support the general consensus observed during CHS that an association exists between the level of cardiorespiratory fitness and improvements in physiological responses to exercise in a hot environment.[67]

2.4 Physical Training

As higher levels of aerobic fitness appear to benefit tolerance to UHS and replicate many of the physiological adaptations reported with heat accli-

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mation, physical training may be an effective complement or replacement for heat acclimation [67,157]. If true, this would be of great interest in many occupational settings, where a temperate ambient environment or lack of facilities may preclude proper heat acclimation. However, aerobic training may differ from heat acclimation both in the nature and the magnitude of the adaptive responses, and the compatibility of these physiological treatments remains an active field of research.

Gisolfi and Robinson[158] were among the first to report a reduction in physiological strain and an improvement in exercise tolerance in CHS environments following a relatively long term (6 weeks) interval training programme. Four weeks of interval training also produced significant improvements in exercise-heat tolerance, with the improvement reaching a plateau after 8 or more weeks of training of approximately 50% of the adaptive responses brought about by heat acclimation.[159]

The effects of shorter or less intense training programmes on exercise-heat tolerance are less clear. Shvartz et al [138] reported that 6 days of training resulted in no adaptations to exercise-heat stress, whereas 6 days of heat acclimation significantly decreased heart rate and core temperature, suggesting also that physical training is not a complete substitute for heat acclimation. Supporting this contention are studies by Strydom et al [160] and Strydom and Williams[161] which reported minimal adaptations to exercise-heat stress following 2 weeks of physical training in a cool environment compared to heat-acclimated volunteers. In contrast, 2 weeks of cycling at 65% $\dot{V}O_{2max}$ produced a significant though slight increase in $\dot{V}O_{2max}$ and was sufficient to elicit an attenuation in cardiovascular and thermal strain during submaximal exercise in a thermoneutral environment.[162] Exercise-heat tolerance was not the focus of this study, and the participants were not tested in hot environments. Houmard et al [163] compared the efficacy of 7 days of training at either 75% $\dot{V}O_{2max}$ for 30 minutes or 50% $\dot{V}O_{2max}$ for 60 minutes on subsequent exercise-heat stress. Compared with pre-training responses, both training programmes produced equivalent and significant decreases in final heart rate and in resting and final core temperature during exercise at 50% $\dot{V}O_{2max}$ in 40°C.

The effectiveness of a training programme in improving exercise-heat tolerance is dependent on many variables, including the intensity, duration and frequency of the training. Henane et al.[151] suggested that a 15 to 20% increase in $\dot{V}O_{2max}$ is required in order to improve exercise-heat tolerance. Metabolic hyperthermia is the major stimulus for thermoregulatory adaptations,[164] and the degree and duration of core temperature rise induced by the training may be a determinant of the degree of heat adaptation. A greater sweating response and heat tolerance was noted following land-based, compared with water-based, training in a group of previously untrained individuals, with the disparity being attributed to the higher level of metabolic hyperthermia and sweating rates during land-based exercise.[132] Kondo et al [165] also reported a higher sweating rate in land-based, compared with water-based, athletes. In addition, individual variables such as genetics, age and the starting fitness of the volunteers would play a role in the final response to training.[157] Havenith[150] has proposed that thermoregulatory improvements in relatively unfit individuals would be greater than in fit individuals following an equivalent improvement in absolute aerobic fitness.

It has been most common for researchers to select environmental conditions that favour evaporative heat loss when work performance in the heat is examined before and after an endurance training programme[151] or when comparisons are made among groups with different aerobic fitness levels.[146] Whether the documented benefits of an increased aerobic fitness on work in the heat would be evident during exposure to more humid environmental conditions that do not favour evaporative heat loss is not as clear. Because the protective clothing restricts evaporative heat loss, it is possible that the increased sweat rate that accompanies an increase in aerobic fitness would have little impact on the rate of heat storage when the clothing is worn.[111] It could be argued that individuals with

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an increased aerobic fitness would dehydrate faster and actually perform worse while wearing the protective clothing if fluid was not provided during the exercise.

Few studies have compared the heat tolerance response of unfit individuals during uncompensable heat stress before and after a controlled endurance training programme designed to improve aerobic fitness. We have examined this response with the use of 2 different training models. Our first attempt used the more classical endurance training model that involved typical progressions in intensity from 60 to 80% $\dot{V}O_{2max}$, frequency from 3 to 4 days per week and duration from 30 to 45 minutes per session over an 8-week period [40]. This training programme increased $\dot{V}O_{2max}$ approximately 15% from 40 to 46 ml/kg/min and produced significant decreases in heart rate and T_{re} responses during 2 hours of compensable heat stress exposure at 40°C and 30% relative humidity as shown below in figures 8 and 9, respectively. In addition, control individuals showed no change in $\dot{V}O_{2max}$ over the 8-week period and no change in their thermoregulatory or cardiovascular response during the 2 hours of compensable heat stress. However, the endurance training programme offered no benefit to the participants during the uncompensable heat stress which involved wearing the NBC protective clothing ensemble. Tolerance times remained unchanged during the heavy exercise at 50 minutes and, as shown in figures 8 and 9, T_{re} and heart rate responses also were unaffected by the training programme. Interestingly, sweat rates were elevated after the training but evaporative heat loss was unchanged when the protective clothing was worn, indicating that the characteristics of the clothing determine the amount of evaporative heat loss to the environment.

Our next approach[101] was to use a short term aerobic training model which had been reported to induce rapid cardiovascular and thermoregulatory changes during submaximal exercise[71,162,166] following 3 to 14 daily aerobic training sessions at 60 to 80% $\dot{V}O_{2max}$ for 1 to 3 hours. We rationalised that in a military environment there may be little

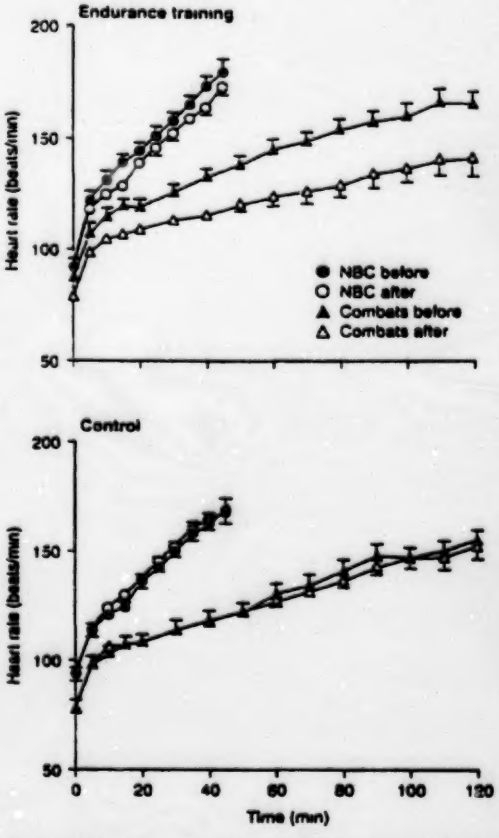

Fig. 8. Heart rate responses before and after 8 weeks of endurance training or no training for men during heat stress exposure while wearing either combat clothing or a nuclear, biological and chemical (NBC) defence protective ensemble. There was a significant decrease in heart rate throughout the heat stress exposure for the endurance trained individuals only while wearing combat clothing [40].

time available prior to deployment to increase aerobic fitness, and also that many military personnel may be unwilling to commit to the long term training required to achieve aerobic fitness levels equivalent to a $\dot{V}O_{2max}$ of 60 ml/kg/min. As a result, unfit volunteers with a $\dot{V}O_{2max}$ below 45 ml/kg/min were evaluated before and after 12 days (6 days per week for 2 weeks) of treadmill walking at 65% $\dot{V}O_{2max}$

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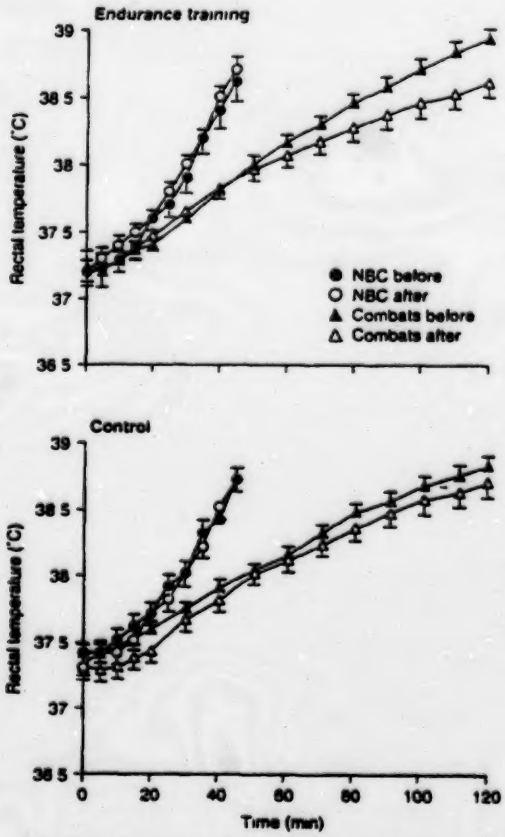

Fig. 9. Rectal temperature responses before and after 8 weeks of endurance training or no training for men during heat stress exposure while wearing either combat clothing or a nuclear, biological and chemical (NBC) defence protective ensemble. There was a significant decrease in rectal temperature after 60 minutes of heat stress exposure for the endurance trained individuals only while wearing combat clothing [40]

for 1 hour each day.[101] The 12 days of training led to significant decreases in the rise in T_{re} and heart rate at the end of the 1 hour of walking in a thermoneutral environment. The small but significant increases in VO_{2max} of 5% were consistent with the changes noted by Green et al [162] using a similar aerobic training model. During the heat-stress test which involved light exercise walking at 3.5 km/h, sweat rate was increased but evaporative heat loss from the clothing ensemble was unchanged after the 12 days of training. In addition, there were no changes in the heart rate or T_{re} responses and tolerance times approximated 90 minutes regardless of the state of training.

The ability of short term aerobic training of moderately fit individuals to replicate the decreased physiological strain and elevated exercise-heat tolerance observed in individuals with a high level of aerobic fitness is of direct occupational interest. In many occupational settings, workers may be required to work in hot environments with minimal preparation time to significantly increase aerobic fitness or facilities to perform heat acclimation through heat exposures. However, our cross-sectional analyses suggests that, when wearing protective clothing, short term aerobic training is not an adequate substitute for a high level of aerobic fitness resulting from habitual exercise and training.[167] We observed that, following 2 weeks of aerobic training, cardiovascular and thermoregulatory strain during UHS were similar in individuals of moderate fitness compared with those of high fitness. However, the range of core temperature that could be tolerated during the heat exposure remained significantly lower in moderately fit individuals, as did the final T_{re} before the onset of voluntary exhaustion and overall tolerance time.

Based on the findings from these studies,[40,101,167] we would have to conclude that aerobic training programmes lasting from 2 to 8 weeks offer little benefit to work performance in the heat for previously unfit individuals when protective clothing is worn. However, the cross-sectional analyses presented above support the importance of aerobic fitness to improve work performance when a very hot and humid microenvironment is created with the wearing of protective clothing. It is also possible that heat tolerance is influenced by genetic factors that also contribute to differences in aerobic fitness.

Therefore, other factors, besides elevations in sweat rates that accompany improvements in aerobic fitness, must be involved in explaining the differences in heat tolerance between aerobically fit

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and unfit individuals. Certainly, the lower resting core temperature[100,151] and the higher core temperature tolerated at exhaustion for individuals with higher aerobic fitness levels[100] are factors that will increase the work time when the protective clothing is worn. As yet, studies that have reported cardiac output measurements while wearing the clothing have failed to differentiate the responses due to fitness level.[30,99] Thus, it is possible that the improvements in cardiac function that accompany long term commitments to endurance training[168] allow greater body heat storage because of the reductions in circulatory strain. In other words, tolerance for less fit individuals may be related more to the strain on the cardiovascular system in its attempt to dissipate body heat and maintain arterial blood pressure, whereas the increase in body heat content may be the greater limiting factor for more fit individuals. In addition, differences in body fatness between fitness groups[100] could account for some of the differences in response during the heat-stress exposure (see section 3.2).

2.5 Interactions

From the above discussion, it is evident that the various physiological manipulations to improve exercise-heat tolerance overlap each other to some extent in their mechanisms of actions and their ultimate effects on the individual. Of the manipulations discussed above, hydration status and adequate fluid replacement appear to have the greatest influence on exercise-heat tolerance while wearing protective clothing, and may have been responsible for masking any potential benefit from aerobic training or heat acclimation.[100,101] Hydration status and its relation to blood volume may also be a major contributor to the improved physiological response and tolerance to UHS in highly fit individuals. Blood volume can range up to 100 ml/kg in trained endurance athletes.[169,170] A high correlation has been reported between aerobic fitness and blood volume,[171,172] though Sawka et al.[173] proposed that this correlation was due to the covariance between $\dot{V}O_{2max}$ and LBM, and that the latter variable provided a better predictor of blood volume.

Similar adaptations occur with exercise training or heat acclimation, making it difficult to isolate the individual effects of training versus thermal stimuli. Furthermore, one manipulation may mask or negate the effects of another. Metabolic heat production and an increase in body heat storage and T_{re} are inherent during aerobic exercise training, further complicating any isolation of factors. The separate roles of thermal versus nonthermal stimuli in the hypervolemic response were investigated by Convertino et al.[174] Similar thermal stresses were placed on 2 groups of volunteers using either exercise at room temperature or sedentary heat exposure. Thermal factors were found to account for 40% of the plasma volume expansion, with the remaining hypervolemia due to additional non-thermal factors related to exercise. Green et al.[175] used 3 days of intermittent supramaximal exercise in an attempt to maximise exercise stress while minimising the confounding influence of thermal stimuli. Total blood volume and plasma volume both increased significantly following 3 days of exercise. Surprisingly, red cell volume was found to decrease, a response atypical of short term training programmes.[172,176] The authors suggested that this alteration in the blood cell population may be due to the particular characteristics of the training programme, which produced a protracted state of metabolic acidosis. Despite the aim of minimising thermal factors, significant thermal stress was still present with this training programme, with T_{re} increasing by an average of 1.3°C over the course of each exercise session.

Aerobic fitness level also appears to mediate the impact of other environmental and individual characteristics. A high aerobic fitness potentiates the sensitivity to heat acclimation and also delays the time course of its decay.[119] Conversely, heat acclimation may mimic the thermoregulatory benefits of a higher $\dot{V}O_{2max}$, though cardiovascular benefits remain.[149] The magnitude of adaptations to heat acclimation may also be inversely related to the initial level of fitness, with a trend towards

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greater decreases in heart rate and core temperature in those with a lower initial VO_{2max} [149] In addition, an increase in aerobic fitness appears to provide some protection against the stress of hypohydration during exercise in the heat due to the reduced cardiovascular stress of exercise.[149] When the same volunteers were exposed to 5% hypohydration, the fitter individuals exhibited a lower heart rate, though no difference was noted in T_{re} [149]

3. Individual Characteristics

Individual characteristics can have a significant influence on the response to exercise-heat stress Gardner et al.[3] reported that the Marine Corps recruits most at risk for developing exertional heat illness during basic training had a body mass index (BMI = mass/height^2) of over 22 kg/m^2 and a time for a 1 5 mile run in excess of 12 minutes at the start of basic training, suggesting an influence of both anthropometric measures and aerobic fitness Interindividual variations in fitness, anthropometric measures and hydration and acclimation status can significantly influence the response to exercise-heat stress when protective clothing is not worn.[147 150,177,178] In contrast, the influence of individual characteristics on the response to exercise while wearing protective clothing is less clear. Since the clothing limits evaporative heat loss, interindividual variations in anthropometric measures or aerobic fitness may have only a minimal influence on determining the level of physiological strain and tolerance Shvartz et al [179] reported that size, surface area and the surface area to mass ratio did not influence the rate of heat storage while wearing vapour barrier clothing in hot environments due to the elimination of a thermal gradient for dry heat transfer and the lack of difference in the rate of evaporative heat dissipation through the clothing. Preliminary stepwise multiple regression analysis on experimental data from our laboratory suggests that, in individuals exercising in the heat with NBC clothing in either an euhydrated or a hypohydrated state, physical fitness (or some genetic factor) was the primary source of variability in physiological responses and tolerance times

3 1 Gender

Results from studies reported some 20 to 30 years ago documented the importance of an increased aerobic fitness[146,166] and a decreased body fatness[180,181] for enhancing tolerance to a hot environment. In addition, Shvartz et al.[179] demonstrated that a larger surface area to mass ratio would be beneficial for thermoregulation during exercise in a warm and dry climate. On average, women typically have a lower aerobic fitness and an increased body fatness compared with males[182,183] Also, the advantage of a larger surface area to mass ratio for radiative and convective heat exchange, as is typically documented for females,[184] disappears in hot climates if the ambient temperature exceeds skin temperature.[179] Thus, based on these characteristics alone, one might expect women to be at a thermoregulatory disadvantage when wearing protective clothing in a hot environment. However, as discussed above, the wearing of protective clothing in a hot and dry ambient environment creates a hot and wet microenvironment within the clothing layers of the protective ensemble which restricts evaporative heat loss. During exposure to hot and humid conditions, Shapiro et al.[183] reported that women of lower aerobic fitness and higher body fatness were at a thermoregulatory advantage compared with males during treadmill walking at 4.8 km/h. This advantage was attributed to the larger surface area to mass ratio for the women, which allowed a more effective evaporative heat loss to the humid environment

We have compared the thermoregulatory responses of men and women wearing protective clothing[185] while performing repeated intervals of 15 minutes of treadmill walking at 4 0 km/h and 15 minutes of seated rest. The rise in T_{re} was slower, the T_{re} tolerated at exhaustion was higher, and tolerance times were extended 25% from 114 to 143 minutes for males who on average had a higher aerobic fitness (49 versus 43 ml/kg/min) and lower body fatness (15 versus 20%) compared with females These findings appear consistent with results from earlier studies which compared thermoregulatory responses between the genders during passive heating or exercise in a hot and dry environment

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when protective clothing was not worn.[183,186-189] A lower S for males was attributed to an earlier onset of sweating[186] and an increased rate of sweating and evaporative heat loss to the dry environmental conditions.[187-189] However, the protective clothing essentially eliminated any advantage of an elevated sweat rate for the males and calorimetric estimates of S revealed no difference between men and women.[185] Thus, we compared the findings to earlier studies that compared the thermoregulatory responses of men and women to hot and humid environments. Both Avellini et al.[190] (who matched men and women for aerobic fitness expressed relative to lean muscle mass) and Shapiro et al.[183] reported that females were at a thermoregulatory advantage compared with males during light exercise and exposure to hot and humid environments. The description of the participant characteristics for the women and men in these other investigations[183,190] was similar to the participants in our study and, thus, could not account for the discrepancies. Therefore, we concluded that the conditions of uncompensable heat stress created with the wearing of the protective clothing could not be compared with the humid test environments imposed by previous investigators.[98,183,190] The HSI was estimated at greater than 2 for our study with protective clothing, whereas this index was calculated at less than 1.25 for these other studies. Thus, it would appear that as the condition of uncompensable heat stress increases in severity, the potential advantage of a larger surface area to mass ratio for increasing evaporative heat loss becomes less evident.

3.1.1 Menstrual Cycle

It has been well established that, under conditions of compensable heat stress, the menstrual cycle affects temperature regulation. Basal body temperature exhibits a biphasic rhythm in which core temperature is approximately 0.4°C higher in the luteal phase compared with the follicular phase.[191-195] Likewise, the core temperature thresholds for the onset of thermoregulatory sweating, cutaneous vasodilation and skin blood flow are also higher in the luteal phase compared with the follicular phase.[190,192,193,195] It is not known whether the same effects hold true under conditions of uncompensable heat stress.

Kolka et al.[196] looked at thermoregulation in women during uncompensable heat stress in the follicular phase alone. Since only one phase of the menstrual phase was studied, conclusions cannot be drawn on possible differences between phases of the menstrual cycle. In a later investigation, Kolka and Stephenson[197] examined the influence of different phases of the menstrual cycle under conditions of uncompensable heat stress. Their main findings indicated that while T_{re} remained significantly higher in the mid luteal (ML) phase compared with the early follicular (EF) phase, tolerance times were similar in both phases (60 and 55 minutes for the EF and ML phases, respectively). They also reported that HR, T_{re}, whole body sweat rate and evaporative heat loss did not differ among phases during uncompensable heat stress.[197]

Tenaglia et al.[198] examined the influence of the EF and ML phases of the menstrual cycle on the cardiovascular and thermoregulatory responses of healthy, young women performing light intensity exercise during uncompensable heat stress. A lighter metabolic work rate was chosen because previous studies done on healthy, young men during uncompensable heat stress had demonstrated that manipulations which lower initial core temperature exert more of an effect on heat tolerance during light intensity exercise of long duration compared with high intensity exercise of short duration.[40,99,128]

The findings of Tenaglia et al.[198] revealed that, like the results of Kolka and Stephenson,[197] T_{re} was significantly higher in the ML phase compared with the follicular phase during uncompensable heat stress (fig. 10). Tenaglia et al.[198] also observed that since delta T_{re} was greater during the follicular phase than in the luteal phase, and the time required for a 1.0°C increase in T_{re} was similar in both phases, there was no phase-related difference in final T_{re}. This suggested that because the women started at a lower initial T_{re} in the follicular phase, and gained heat at the same rate as in the luteal phase, they were able to continue under the uncompensable

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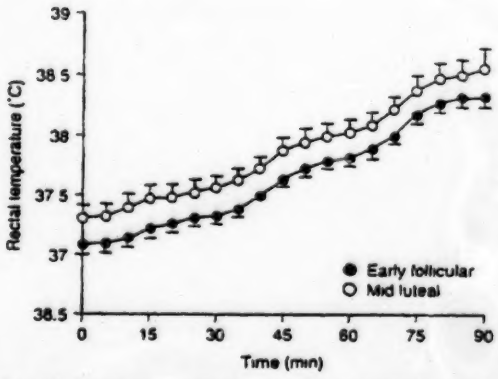

Fig. 10. Rectal temperature responses for females not using oral contraceptives during the mid luteal and early follicular phases of the menstrual cycle during heat stress exposure while wearing a nuclear, biological and chemical (NBC) defence protective ensemble. Rectal temperature was significantly lower throughout the early follicular phase.[199]

heat stress for a longer period of time during the follicular phase before reaching their core temperature threshold for heat tolerance. This conjecture was affirmed by the observation that tolerance times were increased 20% to 128 minutes during the follicular phase versus the 107 minutes recorded during the luteal phase. The fact that menstrual cycle phase affects tolerance times differently depending on the duration of the exercise[197,198] is consistent with studies which have shown that other factors which lower initial core temperature, such as fluid replacement[99] (section 2.1.2), heat acclimation[40,128] (section 2.2) and aerobic training[40] (section 2.4), exert a greater effect on heat tolerance during light exercise of longer duration (> 90 minutes) compared with heavy exercise of shorter duration (< 60 minutes).

Heat tolerance during pregnancy will be reduced because of the continued thermogenic effect of elevated progesterone levels and the progressive decrease in aerobic fitness that occurs (see Gorski[199] and Wolfe et al.[200] for review). In addition, the large increases in core temperature that occur with UHS may place the developing fetus at risk.[199]

3.1.2 Oral Contraceptive Use

Recent investigations have shown that, similar to non-users, resting core temperature is higher during the later stages of the quasi-luteal phase (when exogenous estrogen and progesterone are ingested) compared with the quasi-follicular phase (when the pill contains no exogenous steroid)[201-204] for women using oral contraceptives. The phase-related elevation in core temperature is maintained during exercise in comfortable[202,204] and warm[203] environments, and during passive heat[201] and passive cold[203] exposure.

Tenaglia et al.[198] also examined the influence of oral contraceptive use during uncompensable heat stress. Their results indicated that oral contraceptive use has little impact on the cardiovascular and thermoregulatory responses to uncompensable heat stress. Although T_{re} was initially approximately 0.2°C higher in the quasi-luteal phase, there were no differences in T_{re} between phases by the end of the heat-stress exposure. Also other dependent measures such as $\dot{M}$, HR, mean skin temperature, sweat rate, the rate of evaporative heat loss, heat storage and tolerance time were not affected by oral contraceptive use while wearing the protective clothing. However, compared with non-users, tolerance times were reduced 12% from 128 to 113 minutes during the follicular phase for the women using oral contraceptives.[198] Although these differences did not reach statistical significance, the findings imply that oral contraceptive use may place the woman at a thermoregulatory disadvantage during the quasi-follicular phase of her cycle.

Oral contraceptive use makes the thermoregulatory responses during uncompensable heat strain and the associated tolerance times more uniform across the different phases of the menstrual cycle. The possible mechanism of action of oral contraceptives may be related to the hypothesis proposed by Grucza et al.[202] They hypothesised that the elevation in resting core temperature among women using oral contraceptives is the result of the strong effect of menstrual cycle phase. As such, the elevation in resting T_{re} during the luteal phase of the menstrual cycle may represent a type of circadian

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rhythm that is not altered by the administration of synthetic hormones. Therefore, oral contraceptive use may not result in the resetting of the thermoregulatory setpoint, as is believed to occur during the luteal phase in women with normal menstrual cycles.

3.2 Body Composition

McLellan[135] reported that the partitional calorimetric estimate of S was similar for males and females despite differences in their T_{re} response while wearing the NBC clothing in the heat. These findings imply a different heat capacity of the whole body for males and females. This is not too surprising given the lower heat capacity of fat versus non-fat tissue[181] and the higher body fatness, in general, of females compared with males. Thus, for a given amount of heat production women cannot store as much body heat as men. Previous investigations have revealed little, if any, difference in thermoregulation between the sexes if individuals were matched for fitness, body fatness and/or surface area to mass ratio.[98,190,206] Others have revealed that differences in body fatness, surface area to mass ratio and fitness levels account for over 50% of the variance in heat storage among men and women exposed to dry and humid heat stress.[147,150] McLellan[185] noted that when individuals were matched for body fatness alone or in combination with $\dot{V}O_{2max}$, heat storage per unit of total mass and tolerance times were similar between men and women while wearing the protective clothing. Matching individuals for $\dot{V}O_{2max}$ alone did not equate the heat strain as indicated by the change in T_{re}, tolerance time or estimates of heat storage.[185] Havenith et al.[150] reported that heat storage during exposure to humid heat among 19 men and 8 women was strongly related to $\dot{V}O_{2max}$ ($r = -0.85$) or the relative intensity represented by cycling at 60W ($r = 0.88$). However, their estimate of heat storage was determined by thermometry assuming the same average heat capacity of the body for all individuals. This assumption may not be appropriate given the variation in body fatness among individuals and the lower heat capacity of adipose tissue.[207,208] McLellan[185] also reported that when volunteers, regardless of gender, were grouped according to their final T_{re}, the group with the lower T_{re} and shorter tolerance times had the lower $\dot{V}O_{2max}$ and higher body fatness. These findings supported the data described for the comparisons between the sexes and led to the general conclusion that body composition and aerobic fitness had a significant influence on heat tolerance while wearing the protective clothing and performing light intermittent exercise in a hot environment.

3.3 Circadian Rhythm

The normal circadian rhythm leads to oscillations in resting core temperature that can vary by 0.5°C from early morning to mid-afternoon.[209] If the core temperature tolerated at exhaustion does not similarly show a circadian effect, then the higher resting core temperatures in the afternoon should reduce tolerance time while wearing the protective clothing. However, McLellan et al.[210] observed in a recent study that trials conducted in the early afternoon were associated with an increased T_{re} tolerated at exhaustion that offset the circadian influence on resting T_{re} and, thus, maintained tolerance times similar to trials conducted in the morning. Given that other effector responses, such as the temperature threshold for the onset of sweating and skin vasodilation, occur at higher temperatures in the afternoon compared with the morning,[211] it is possible that the T_{re} tolerated at exhaustion is also regulated at a higher temperature in the afternoon. This interpretation implies that it is not an absolute core temperature that the body can tolerate before exhaustion occurs, but rather a given increase in body heat content or delta core temperature. Webb[34] has proposed that the body regulates heat content rather than core temperature, and the results from the recent study by McLellan et al.[210] would be consistent with Webb's theory of heat regulation. However, as we have stated earlier in this review (see sections 2.1.1, 2.2, 2.3 and 3.1.1), there are certain conditions where a change in the resting core temperature alters total heat storage when protective clothing is worn. For example, factors such

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as aerobic fitness[100] and heat acclimation,[128,129] which lower resting core temperature, are associated with an increased heat storage and tolerance time. Conversely, factors such as mild hypohydration[100,101] or the post-ovulatory phase of the menstrual cycle,[197,198] which raise resting core temperature, lower total heat storage and reduce tolerance time. In addition, Gonzalez-Alonso et al [212] recently reported that well trained cyclists fatigued at the same core temperature of approximately 40°C during UHS regardless of changes to the initial core temperature or rates of heat storage. What accounts for the ability of the body to alter heat storage under some conditions and not others is unclear at this time.

3.4 Age

Pandolf[213] and Kenney[214] have recently summarised the effects of the aging process on temperature regulation. Their overwhelming consensus was that declines in aerobic fitness, rather than the aging process *per se*, were responsible for differences in the thermoregulatory responses of older individuals compared with their younger counterparts. Certainly, if older and younger individuals were matched for aerobic fitness and body fatness (as discussed above for the comparisons between men and women), there would be no reason to expect a difference in work performance in the heat while wearing the protective clothing.

4. Conclusion

The wearing of protective clothing in warm or hot ambient conditions significantly increases the thermal stress on an individual. The protective clothing ensemble creates a barrier to heat exchange between the body and the environment which significantly impairs the individual's ability to dissipate metabolic heat. During uncompensable heat stress the body continues to store heat and, thus, special precautions must be taken to minimise the threat of thermal injury in those athletic and occupational settings where protective clothing is worn.

The primary and most effective countermeasure is ensuring that the individual is adequately hydrated both before and throughout the exercise or work session. Even relatively minor levels of hypohydration prior to exercise will significantly increase physiological strain and decrease exercise tolerance. Similarly, even moderate levels of fluid ingestion during exercise decreases physiological strain and increases exercise tolerance. This is in consensus with research done on compensable heat stress environments. In contrast, neither short term aerobic training nor heat acclimation significantly improved exercise-heat tolerance during uncompensable heat stress. While short term aerobic training is relatively ineffective, long term improvements in physical fitness appear to provide some degree of protection. In addition to decreased physiological strain, one major adaptation in the highly fit was an ability to tolerate higher core temperatures before voluntary exhaustion. Body composition also appears to have a major impact on heat storage capacity and heat tolerance. Individuals with a higher body fatness have a reduced tolerance. For women not using oral contraceptives, heat tolerance is reduced during the luteal phase of the menstrual cycle. In contrast, heat tolerance is similar throughout the menstrual cycle for women using oral contraceptives. Finally, at least for trials conducted in the morning and early afternoon, it appears that heat tolerance is not affected by the diurnal oscillations in resting core temperature.

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